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The critically refracted longitudinal wave (CRLW) technique was used to establish how feasible it is to measure stress changes at the surface and interior of a material, in particular naval airframe metals such as Ti-6Al-4V, 6061-T651 Aluminum, and 4340 steel. The CRLW propagation characteristics were found to be potentially practical if use of the 2P wave is implementable to have it as a reference wave. The CRLW technique was effective in detecting stress gradients in bent plates by measuring the acoustoelastic effect on the longitudinal wave velocity. The CRLW technique was applied in the range of 1.0 to 10 MHz and the expected longitudinal wave velocity changes followed the expected trends in the Al6061-T651 and 4340 steel plates (0.50 inch thick). The longitudinal wave velocity changes measured in the Ti-6Al-4V plate did not follow the expected trends probably due to its thickness (0.25 inch).

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PHASE I - FINAL REPORT

"Surface Residual Stress Analysis of Metals and Alloys"

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By:

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TABLE OF CONTENTS

1.0 INTRODUCTION

Engineering materials commonly used in metallic naval airframes have, before they are put in service, been manufactured to meet and/or exceed design considerations. During the manufacturing process, these materials are inevitably going to be non-homogeously deformed such that residual stresses will be induced at the surface and the interior of the materials. In order to assure that the design considerations will be met, a quantitative and accurate assessment of the surface and the interior residual stress must be performed. Precisely knowing the residual stress level and distribution is of paramount importance since residual stress will be added to the service stress. Thus, a quantitative evaluation of residual stresses at the surface and in the interior of structures and components using an ultrasonic technique was investigated in this Phase 1 Project.

There are currently several commercially available instruments capable of measuring residual surface stresses based on x-ray diffraction or magnetic methods. The x-ray diffraction methods are time consuming and difficult to apply in confined areas with associated limitations due to safety considerations. The magnetic methods are only appropriately used in ferromagnetic materials. This project illustrates the feasibility of an ultrasonic method devised to asses the effects of texture, microstructure, acoustoelasticity, and residual stress in metals (ferrous and non-ferrous alloys).

Residual stresses in general vary throughout the thickness of a part, so it is important to have a means of measuring surface and interior residual stress to assure that net stress levels within a part when it is put in service or already in service will be in tolerable levels. The method proposed herein is based on the Critically Refracted Longitudinal Wave (CRLW). Previous research on the CRLW method showed that the depth of penetration of the longitudinal wave used in this method is frequency dependent[1, 2]. Also, the CRLW wave propagates parallel to the surface of the part under examination in a volume just below the surface, producing a truly subsurface wave. This means that it should be possible to measure stress at the surface, as well as, as a function of depth from the surface by characterizing the frequency components of the CRLW wave spectrum.

2.0 CRITICALLY REFRACTED LONGITUDINAL WAVE (CRLW) TECHNIQUE

2.1 Literature Survey

A literature survey was conducted to update the latest developments in residual stress measurements techniques, as well as, instrumentation available for potential development in Phase II. The result of this survey is listed in the bibliography and reference sections of this report. Some of the instrumentation and methods that could be applied to the CRLW technique are the velocity measurement method developed by Wormley et.al. [3] and the implementation of Electromagnetic Acoustic Transducers (EMATS) to develop a non-contact technique. EMATs have been used for stress measurement applications generating Shear Horizontal Waves (SHW) [4] and are likely to be used to generate CRLW.

2.2 Wave Propagation Model

The model proposed for understanding the propagation characteristics of the CRLW was developed using geophysics wave propagation algorithms. The model was scaled to produce results in the 0.5 MHz to 10 MHz range, and is based on the wave mechanics of head waves, lateral waves, and the full range of inhomogeneous waves generated in layered material.

A. Numerical calculation of waveforms

In order to provide an improved understanding of the observed waveforms seen in the physical experiments, the expected waveforms for uniform and varying distributions of elastic wave

velocities in plates have been calculated. The numerical technique used is called the reflectivity method [5], which is a common technique used by seismologists in the calculation of synthetic seismograms in flat layered media.

The reflectivity method is well-suited to representing the problem of elastic wave propagation in more-or-less plate-like structures when the source and receiver are both on the same side of the plate. The fundamental assumptions in the reflectivity method are:

1. Material properties vary only with depth (coordinate normal to plate)
2. The medium is overlain by a uniform halfspace.
3. The medium is underlain either by a uniform halfspace or by a rigid or free boundary.

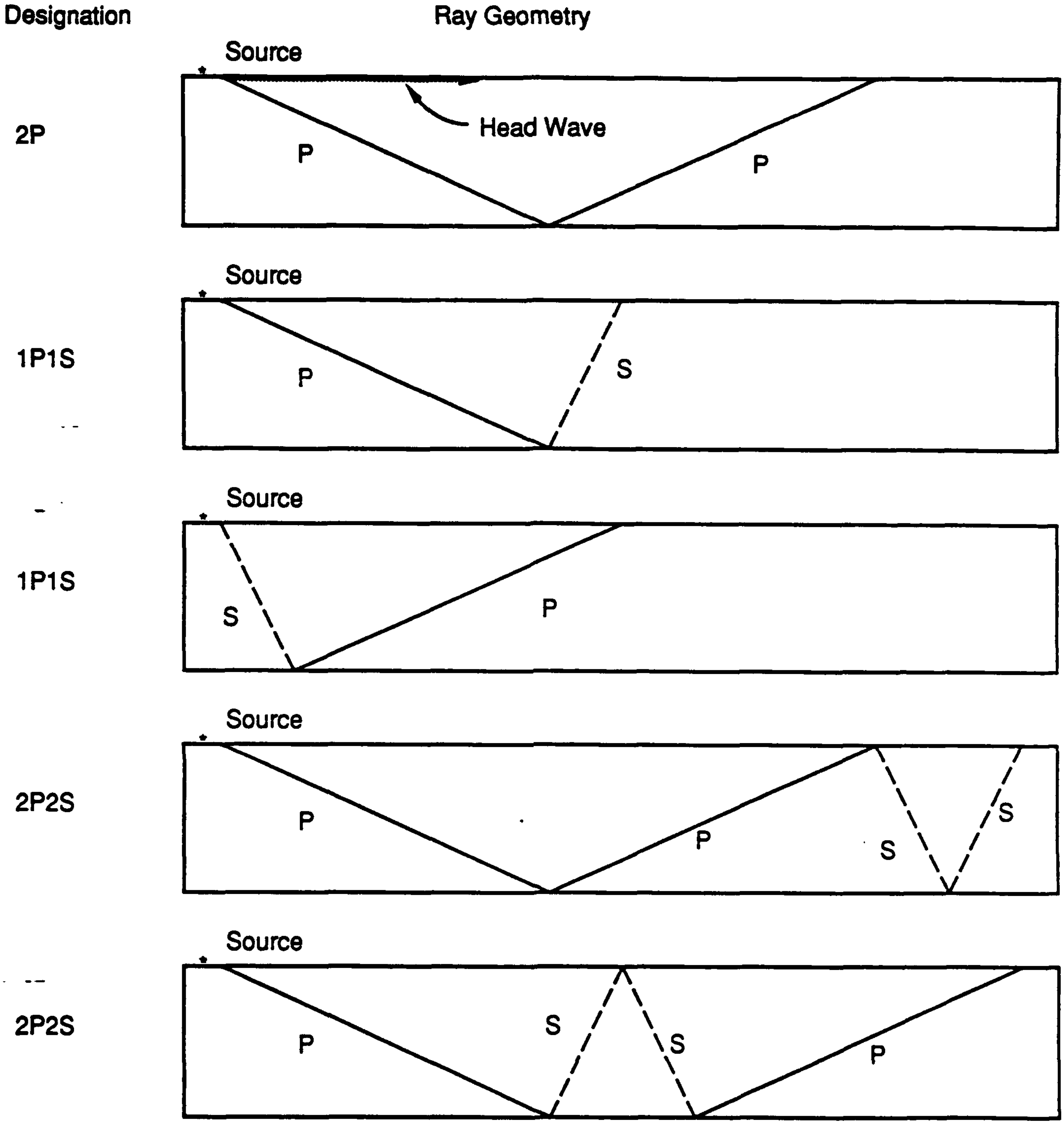
The first assumption ensures that the equations of motion are separable. A Fourier decomposition of the differential equations into the frequency-wavenumber domain. The second and third assumptions ensure that the generalized reflection coefficient obeys a simple recursion formula. In the acoustic case the reflectivity is a scalar function, but in elastic problems the reflectivity is a matrix. For instance, in isotropic media, the propagation of coupled compressional waves and vertically polarized shear waves (called the P-SV problem in seismology) separates from the propagation of horizontally polarized S waves (the SH problem). The SH problem then yields a scalar reflectivity function, while the P-SV reflectivity is a 2x2 matrix containing four generalized reflection coefficients: P-to-P, P-to-S, S-to-P, and S-to-S. The reflectivity is a 3x3 matrix in the general anisotropic case. An isotropic medium has been assumed to perform these calculations.

In the simplest case, all sources and receivers are in the upper halfspace, as in the physical experiments. The upper halfspace is a fluid with the elastic properties of air. The plate is bounded on the bottom by an elastic halfspace that is also similar to air, but which has a very small rigidity. The plate is represented by a single layer if it is uniform, or by many layers if its properties change with depth. The algorithm requires that the medium be piecewise constant, but layered representations of smooth velocity variations are accurate so long as the layers are unresolvably thin at the frequencies of interest.

The source is specified by a given bandwidth in temporal frequency and a range of phase slownesses (reciprocal of phase velocity). Wavenumber is frequency times phase slowness, so that the wavenumber range at each frequency is proportional to frequency. The use of slowness dependence is computationally efficient, since the interface plane-wave reflection coefficients and the layer propagation delays depend only on slowness and need not be recalculated when the frequency changes. The choice of a frequency-independent intrinsic attenuation makes this simplicity possible. The response is recovered as a function of space and time by a double or triple Fourier transform.

For point-source problems in isotropic or transversely isotropic media, the Fourier-Bessel transform from the wavenumber to the distance domain with an asymptotic approximation to the Hankel functions is used. The results in this report are for point sources and isotropic plates.

The synthetics show the vertical displacement response for an explosive source just above the plate. The response is given as a function of time and of distance from the source. A pulse that appears at the same (reduced) time across the set of traces actually has a phase velocity equal to the reducing velocity (6.3 mm/microsecond for aluminum). Arrivals that appear progressively earlier as distance increases on this plot are faster than the reducing velocity. The large and very fast arrival near the origin is a numerical artifact due to the truncation of the slowness (wavenumber) integrals. There are also some very slow arrivals at large distances and small times. These are caused by the temporal wraparound of the fast Fourier transform, and they are already suppressed as much as is practical. The first real arrival is the headwave (CRLW). (see Figures 1, 2, & 3). It is centered at reduced time = 0 (the acausal pulse is due to the zero-phase spectrum of the source), and it fades



Ray nomenclature.
Path 2P is unique.
Both possible 1P1S paths shown.
Two of the six possible ray paths for 2P2S are shown.

Figure 1. Ray geometry and designation utilized in the modeling of the CRLW propagation in a plate.

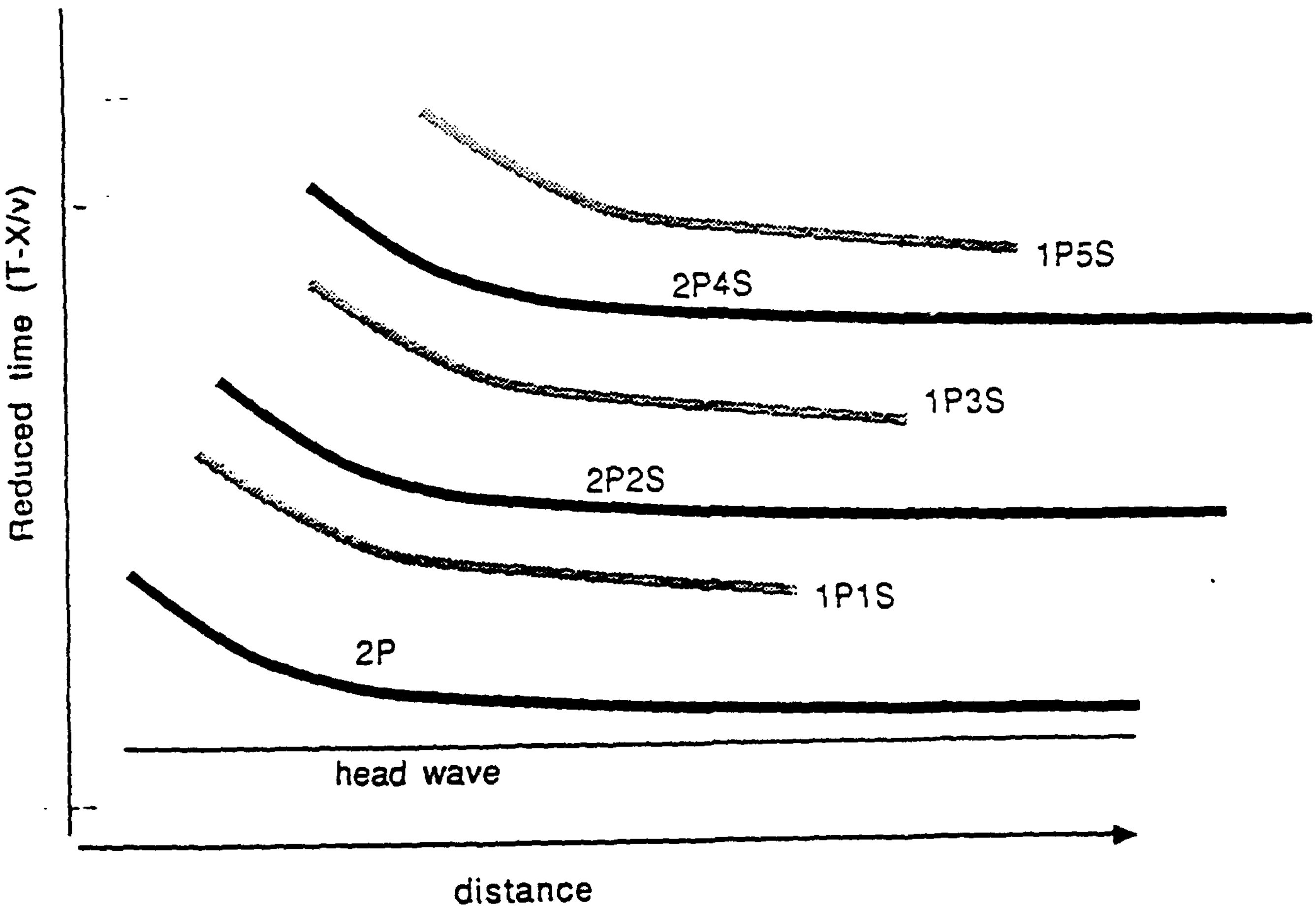


Figure 2. Major phases in synthetic modeling. Head wave is typically weak. Phases that have travelled through the body of the plate and reflected from boundries are stronger. 2P is P wave reflected from bottom of plate, signifying 2P wave ray segments. 1P3S has two reflection points on the bottom and one from the top boundry, consisting of a single P ray segment and 3 S ray segments.

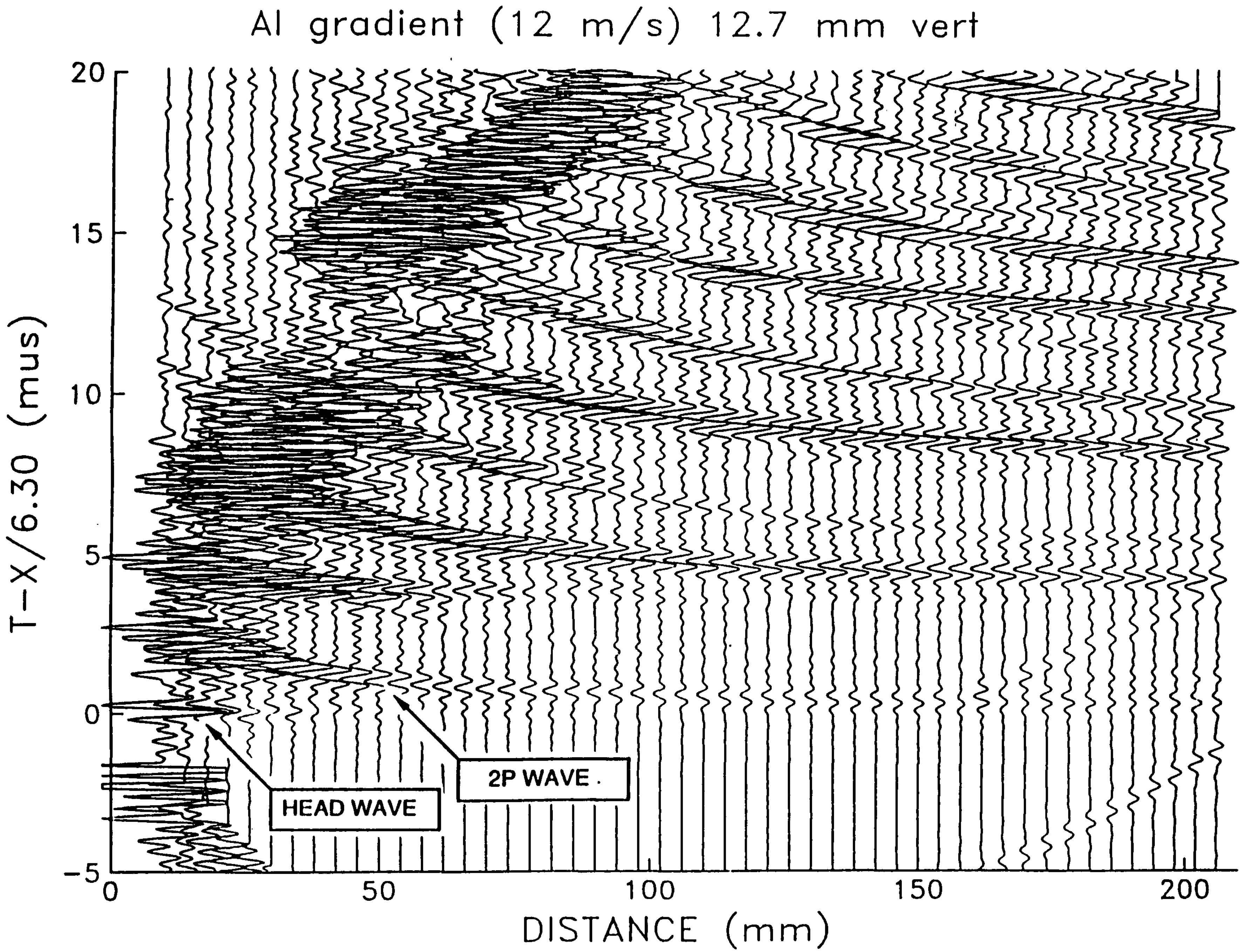


Figure 3. Seismogram style plot for Al-6061-T651 plate waves in a 0.050" thick plate.

quickly with distance. The first prominent arrival is a P wave that has been reflected from the bottom of the plate. This phase is denoted 2P to indicate that the raypath consists of two P ray segments. The next large arrival is a combination of a P wave reflected as an S wave and an S wave reflected as a P wave. This phase is denoted as 1P1S, meaning one P ray and one S ray. Associated with this phase with nearly constant spacing in time are the arrivals 1P(2n+1)S, where n = 0,1,2,... In general, this family contains ray systems with odd numbers of P rays and odd numbers of S rays, but the multiple-P ray versions are very close in time to the 1-P versions, or they are much weaker. After 1P1S but before 1P3S, there is another strong arrival denoted by 2P2S, with the meaning of two P ray segments and two S ray segments. Interleaving the 1P(2n+1)S arrivals is the family 2P(2n)S. Note that the total number of reflected ray segments is always even, since the total raypath must begin and end at the top of the plate.

The comparisons of the heterogeneous and uniform plate models show only the subtlest changes. In the case of a simple linear increase of velocity from one face of the plate to the other, as might arise from a flexed plate, the effects are essentially invisible. Interestingly, the case where the velocity is higher or lower in the center than at the faces of the plate, as might arise in case-hardening or other special tempering techniques, shows very visible changes in waveform amplitudes, especially in the 2P phase. We note in passing that the Born approximation [6] for scalar wave propagation grossly predicts these effects. In this approximation, a weak linear gradient transverse to the direction of propagation has no first-order effect on traveltime or amplitude. However, the same approximation predicts first-order effects if there is a quadratic variation. In effect, the low or high velocity channels in the centerplane of the plate provide quadratic-like variations that are detectable in acoustoelastic experiments.

Generally, the synthetic studies show that:

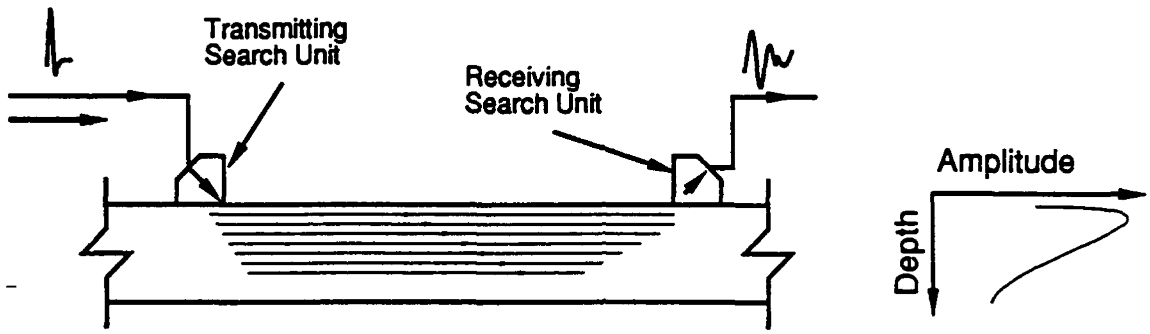
1. Travel-time changes due to velocity effects from stresses are usually very small
2. Headwaves are very weak
3. Multiply-reflected waves are identifiable and dominate the observations.
4. Waveform phase and amplitude changes may be helpful diagnostics of residual stress.
5. Relative stability of later part of seismogram may be helpful in removing source and receiver effects.
6. Broadband source and receiver arrays provide the most useful data

2.3 Expected Effects of Transducer Frequency and Size

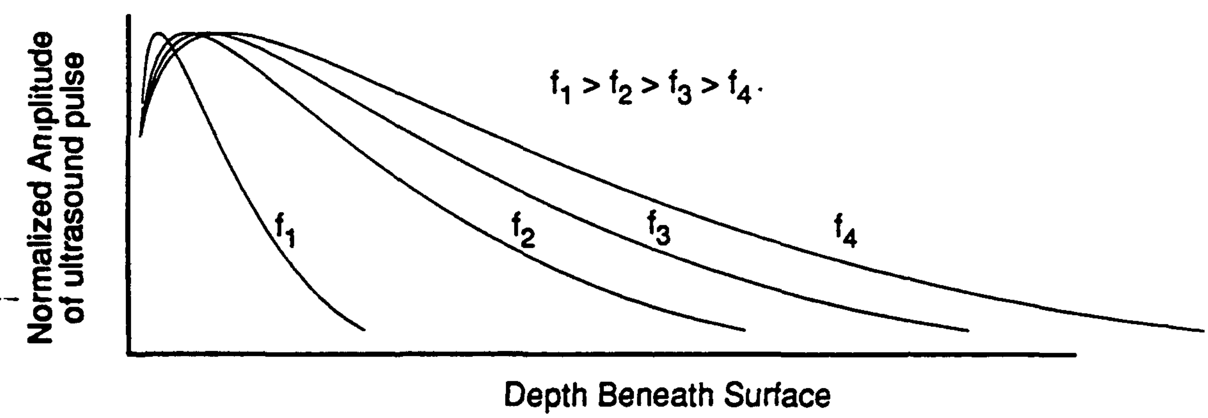
In reference [2] it is theoretically shown that the refracted angle of the CRLW increases as the product of the frequency x diameter (f • d) of the generating search unit increases. By increasing the angle of refraction, the CRLW main lobe of pressure will move closer to the surface. This effect can be achieved by maintaining the size of the generating transducer constant and varying the transducer frequency, as shown in Figure 4. Lower frequencies will penetrate deeper inside the material while higher frequencies will stay closer to the surface, creating a potential for measuring material related changes as a function of depth. For example, to measure stress either applied or residual as it changes through the thickness of a part or structure.

In the present case, two different experiments were designed to produce the following: (1) a state of stress through the thickness of a plate that is uniform, and (2) a state of stress through the thickness of a plate that is changing.

In order to achieve a uniform state of stress (1) a tension test was performed and a varying state of stress, and (2) a four point bending test was performed.



(a) Generation and detection of CRLW (Creeping Wave) ultrasound. Horizontal lines are perpendicular to the wave front.



(b) Variation in CRLW ultrasound amplitude with depth and frequency.

Figure 4. CRLW Ultrasound Method for Measuring Stress and Variation of Frequency to Achieve Depth Scanning

The expected results should establish if the CRLW is sensitive to stress changes as follows: In a tension test where the state of stress through the thickness of a plate is uniform (see Figure 5), the stress effect on the CRLW is expected to be the same regardless of the test frequency. It may, however; produce a slight effect due to sampling volume of the bulk wave, i. e., larger sampling volume for lower frequencies. In a four point bending test where the movement is uniform between the middle supports (see Figure 5), the stress through the thickness reverses at the middle of the thickness. The stress effect on the CRLW is expected to be more pronounced at the higher frequencies and at a minimum at the lower frequencies.

If no significant relative phase shifts are obtained, this would suggest that the hypothesis that stress changes in the interior of the specimen are reflected as phase shifts in the frequency components in the received CRLW pulse should be rejected.

3.0 EXPERIMENTAL SETUP AND TESTS

Ultrasound is an ideal probing field for surface and interior stress measurement since it has the required material penetration capability. The CRLW technique is based upon measuring the velocity of longitudinal waves that travel parallel to the surface of test specimens to be evaluated for residual stress.

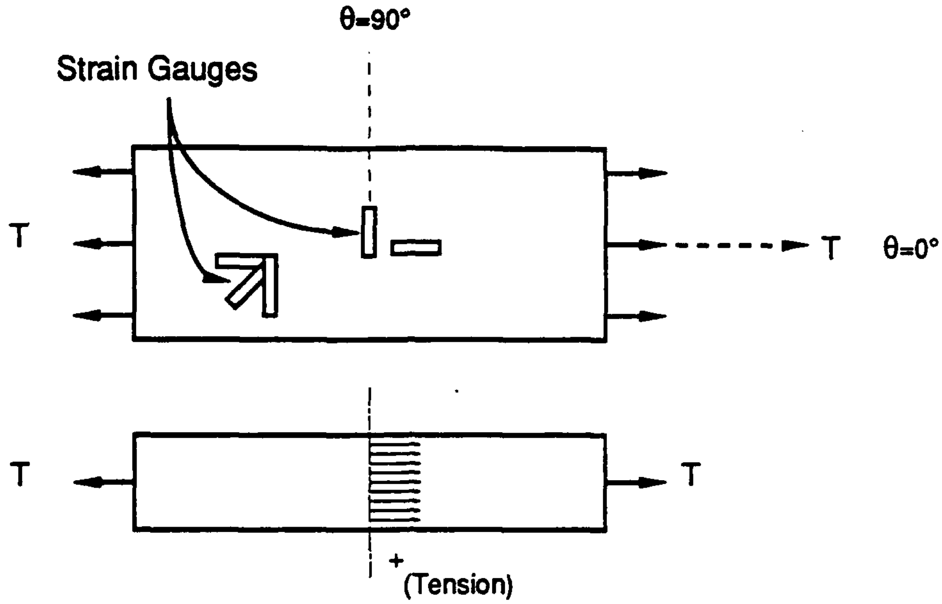
The CRLW technique inveigated may be able to measure residual surface and interior stress incorporate frequency scanning of depth based on longitudinal waves that travel below and parallel to the surface of the specimen. These waves, often called creeping waves, appear when the incident angle of ultrasound on the surface of the test piece is set to the value of the first critical angle.

In a two media arrangement (upper and lower medium) the CRLW wave is excited in the lower medium by having an ultrasonic beam in the upper medium impinging on the boundary at the first critical angle in accordance with Snell's Law. The proposed CRLW technique uses an ultrasonic probe consisting of three search units; one is used as a transmitter and two as receivers of ultrasound. The search units are mounted on plastic wedges (upper medium) machined so as to transmit and receive the CRLW wave that propagates near and parallel to the surface of the part under test (lower medium). A special fixture is used to maintain a constant gauge length between the receiving search units. An alternative to this arrangement is to use only one transmitter and one receiver probe.

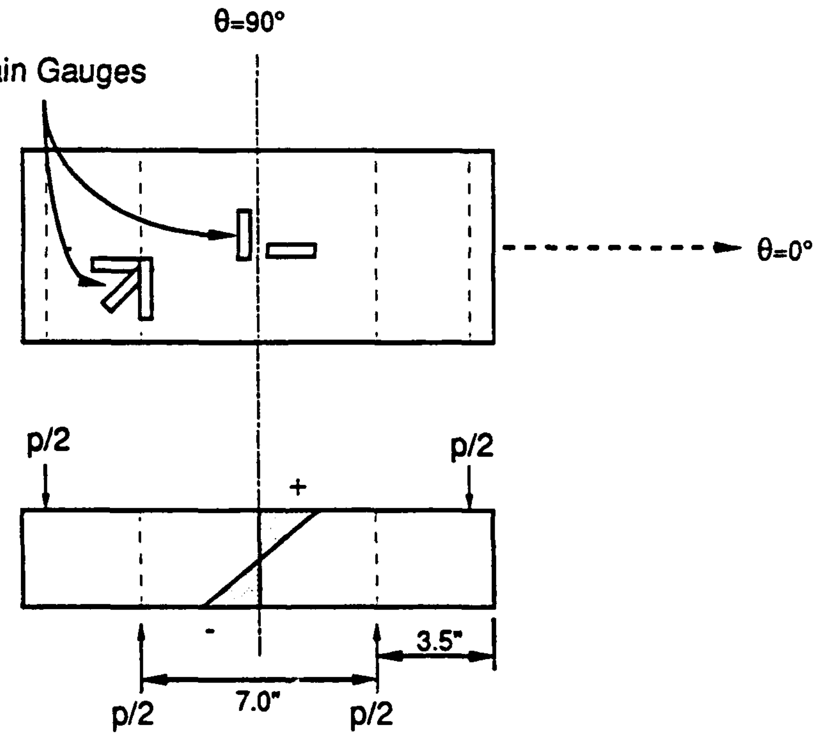
Variation in ultrasound travel time with stress state is used as a measure of the component of stress lying along the direction of the longitudinal axis of the probe. Sampling depth is adjusted by either (1) changing the frequency of the injected ultrasound or (2) changing the size of the piezoelectric element in the search units [1].

From references [1,7], it is known that CRLW ultrasound velocity varies linearly with the component of stress lying in the propagation direction of the waves.

The CRLW frequency scanning technique is executed in the following way. Broad-band search units are used as a transmitter and a receiver of ultrasound. They are mounted accurately at a fixed gauge length apart. Whenever the transmitter is excited with a sharp pulse, it produces a near delta-function CRLW wave in the test piece. The Fourier transform of the resulting CRLW wave contains a broad band of frequencies. The frequency content, together with phases and amplitudes, are obtained by Fast Fourier Transform (FFT) computer methods. Phase shifts in the frequency components are related to corresponding velocity shifts due to stress variations with frequency and, therefore, with penetration depth. An alternate technique utilizes sets of transducers of a known central frequency and travel-time is measured by identifying the first positive zero crossing of the first pulse arriving after the initial pulse. This arrival corresponds to the CRLW or headwave.



(a) Flat plate in tension to obtain constant stress througn thickness. Double arrows show orientation of search unit fixture.



(b) Flat plate subjected to 4-point bending to obtain linear change in fiber stress from tension to compression. Double arrows show orientation of search unit fixture.

Figure 5. Linear and 4-Point Bending Tests Using Flat Plate Specimen

3.1 CRLW Probe and Wave Form Characterization

Flat-plate materials used for this project had the following physical characteristics:

Table I. Test Plate Physical Characteristics

Material Specification	Plate Dimensions L (in)	W(in)	T(in)
Ti-6Al-4V	16	6	0.25
Al-6061-T651	16	6	0.50
4340 Steel	16	6	0.50

Sets of broad band search units with frequency centered at 1.0 MHz, 2.25 MHz, 5.0 MHz, and 10 MHz and a useful band of 500 KHz to 5 MHz were employed. This range of frequencies gives rise to CRLW with penetration depths varying from near surface (5 MHz) to 0.45-inch (500 KHz) depending on the velocity of the material.

A probe fixture for holding the search units at fixed distance was designed and built such that it was adaptable for use in curved (cylindrical surfaces). Figure 6 shows the experimental setup using a Austin Computer 386/33 MHz PC (personal computer), including an STR*8100 MHz analog to digital board.

Amplitude of the CRLW ultrasound pulse as a function of depth and of frequency were measured to confirm the effect of frequency on depth of penetration. The transmitter was located on the top surface of a plate. The receiver, a small diameter unit, was used to sample the CRLW ultrasound present at an end face. Baseline or initial velocity measurements were performed in all the test plates as a function of orientation with respect to the rolling direction (0 °) of each plate. It was found that for the Aluminum 6061-T651 plate the CRLW attenuated considerably at 45° orientation, and at 10 MHz frequency. In addition, the longitudinal wave velocity was found to decrease at approximately 45° orientation for the Aluminum 6061-T651 plate and the Ti-6Al-4V plate. For the 4340 steel, the longitudinal wave velocity was larger at 90° orientation and it decreased gradually towards the 0° orientation.

3.2 Tensile Test

The loading arrangement is shown conceptually in Figure 7. The plates are fixed in a tensile testing machine. Strain gauges are attached to them. The probe fixture is mounted on the plate under test, aligning it sequentially along lengthwise (0°) crosswise (90°), and 45° angle axes. In this test, a set of one transmitter and two receivers are used to measure the CRLW velocity. The distance between the second receiver is approximately 116 mm.

Broad-band pulses were injected into the plate using the transmitting search unit and the received pulses were displayed and also stored. The received pulses were analyzed to obtain travel-time and amplitude information. Then the plates are loaded in tension, and the resulting received wave-forms are recorded and subjected to analysis.

The relative travel-times of the frequency components should be independent of applied load since the applied stress should be independent of depth in the plate for the loading method used. However, there should be travel-time shifts of the frequency components proportional to load. This would be a manifestation of the acoustic elastic effect. By measuring these travel-times as a function of applied stress, the acoustic-elastic coefficient is obtained. This coefficient gives the

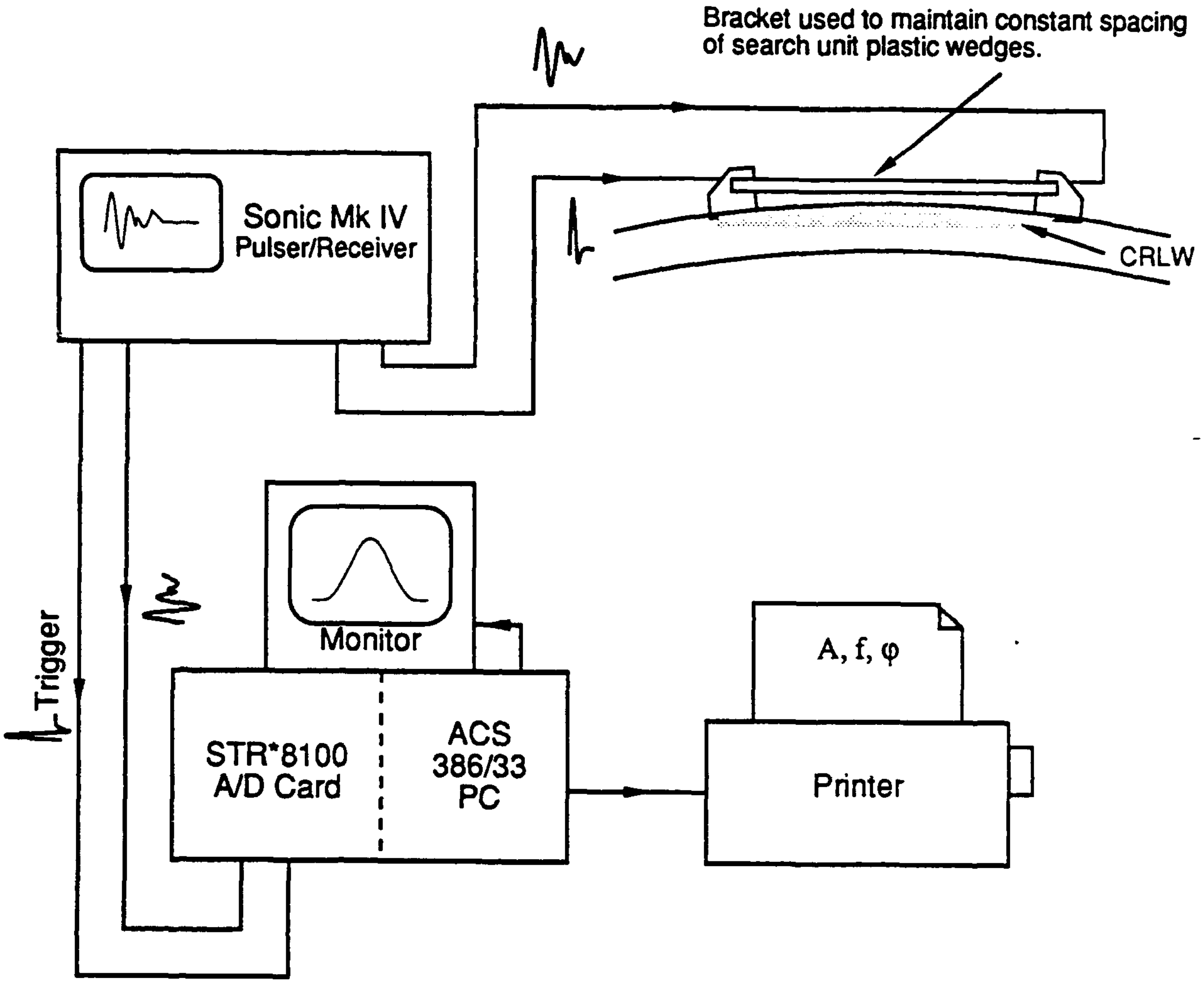
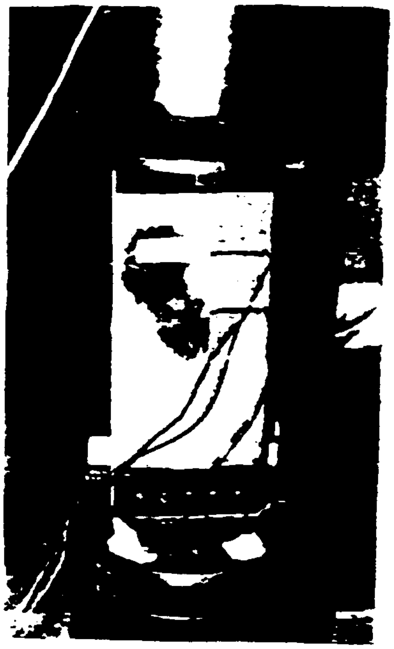
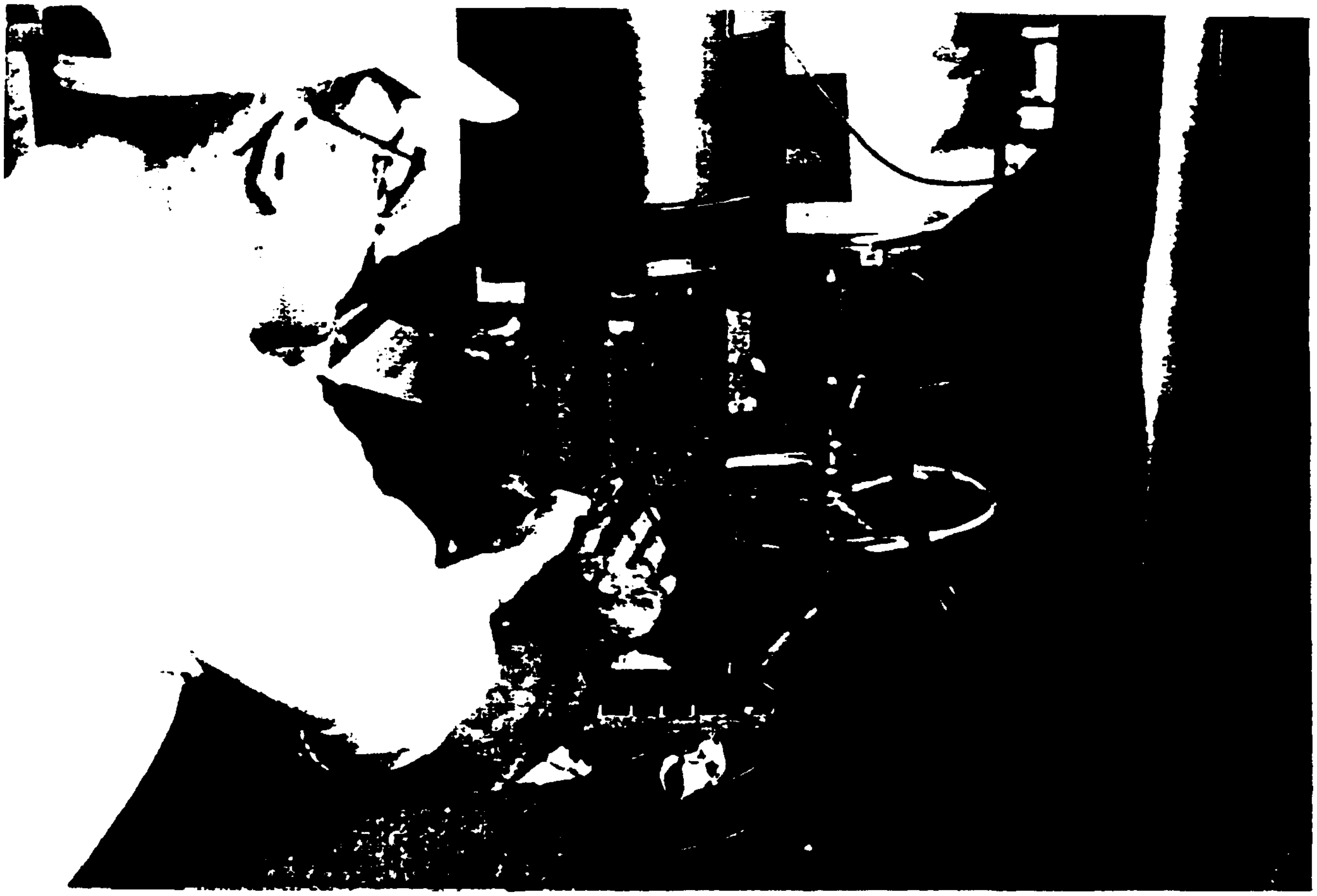


Figure 6. Instrumentation Set -Up for CRLW Stress Measuring Method

(Right) Strain gauge rosettes mounted on test plate measure strain parallel (0°), perpendicular (90°), and 45° from applied load axis. The ultrasonic probe is placed on opposite side of plate (as shown below)



(Below) Technician holds ultrasonic transducer module on test plate at 0° orientation or parallel to applied force, during load tests at Texas A&M Engineering Laboratory



(Above) Ink marking on 16 inch long x 6 inch wide x 1/4 inch thick titanium test plate indicating the 0°, 45°, and 90° orientations to position ultrasonic probe fixture.

Figure 7. Strain gauge and ultrasonic velovity instrumentation on test plates used to evaluate CRLW ultrasonic stress measurement technique, December, 1991.

relation between stress and phase shift (travel-times) when the stress through the thickness of a specimen is constant.

3.3 Four Point Bending Test

A 4-point bending fixture was constructed. As shown in Figure 8, this means of stressing creates a linear change in stress through the test plate (tension from compression). The fiber stress at any depth will be constant along the length defined by the inner two bending points on the fixture. Loading was applied with an hydraulic press. Surface strains are measured with the aid of strain gages and internal stresses are computed from the measured strain values. The load applied was measured with a load cell (10,000 lb capacity). The load was then applied by two rolls separated 14 inches apart in a downward motion. The maximum deflection at the middle of the plate was measured as the load was applied.

Received ultrasonic wave forms (see Figure 9)were recorded and processed during the tensile test to obtain travel-time versus frequency data. If the travel-time of the components are shifted relative to each other as stress is applied, this would mean the different frequency components are "seeing" stress changes as a function of depth. The probe arrangement used in this test consisted of one transmitter and one receiver spaced 100 mm apart.

4.0 RESULTS AND ANALYSIS

4.1 Tensile Test

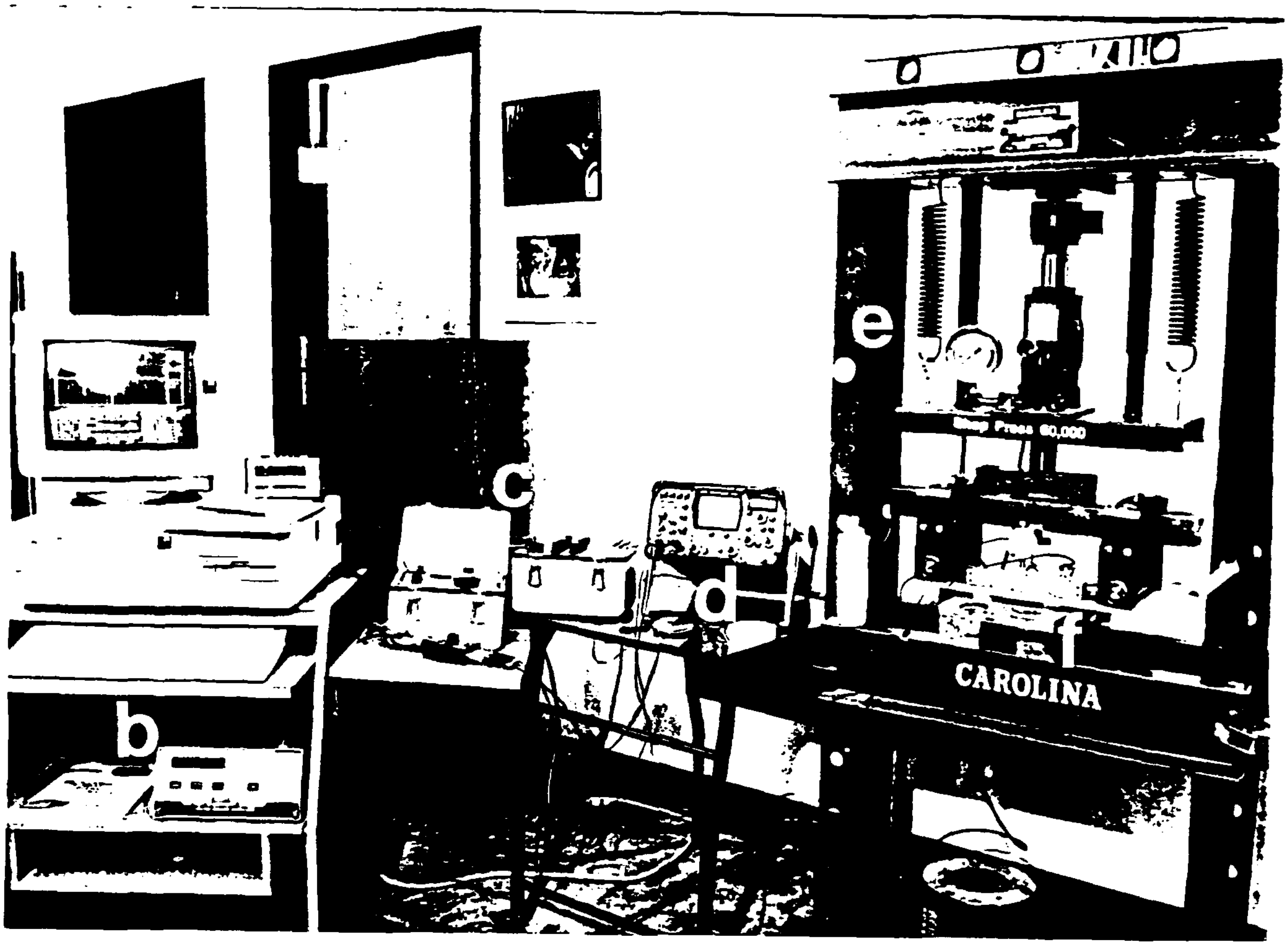
The acoustoelastic constants were obtained from the data collected from the tension test, the results of which are listed in Table II. The data in Table II indicates that for the 0 ° measurements (parallel to the applied force), 4340 steel has the largest effect; aluminum 6061-T651 is smaller than 4340 steel but it is also larger than for Ti-6Al-4V which has the smallest effect. Figures 10 A-C show the plots of the percent velocity change versus tensile strain at room temperature (60 ° F.) for each of the frequencies used during the test, i.e., 1.0, 2.25, 5.00, and 10 MHz. The slope of each line represents the acoustoelastic constant. The measured maximum tensile strain (shown in Figures 10 A-C) was produced by applying a tensile load of 50,000 pounds.

Figure 10 A (Ti-6Al-4V) shows the linearity of the acoustoelastic effect better than either aluminum alloy 6061-T651 or 4340 steel. These deviations from linearity are probably caused by contact problems encountered during the test when Ultragel II (registered trademark by ECHO Ultrasound) couplant was used.

The 45 ° acoustoelastic constants for all the materials and frequencies had the tendency to be higher except for 4340 steel at 1 MHz. For the 90 ° there was no measurable change detected in the 4340 steel, small effect detected in the Al 6061-T651 with no change detected by the 10 MHz frequency. The 90 ° data collected for the Ti-6Al-4V shows dramatic to no changes, probably caused by the highly attenuated signal found at this orientation causing an increase in instrument gain creating a very noisy signal.

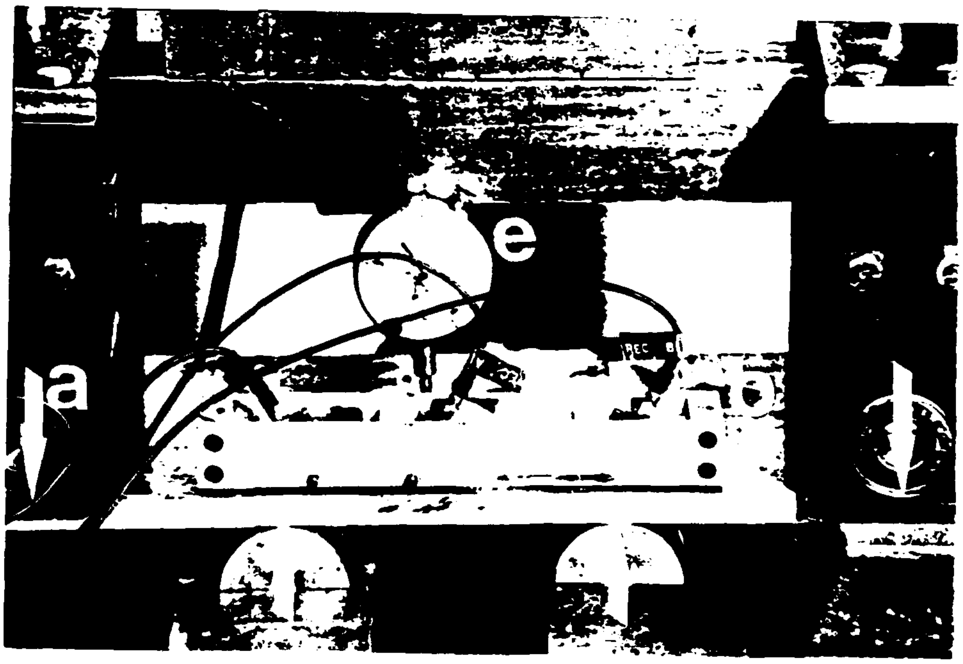
4.2 Four Point Bending Test

The 4-point bending test results are shown in Figures 11 A-C and Table III. The plots show the longitudinal wave velocity change as a function of applied (measured) load. The data initially collected using Ultragel II as couplant showed to have poor repeatability. After trying different kinds of couplant, it was found that water helped enormously to improve repeatability. The plots shown in Figures 11 A-C were obtained by placing the ultrasonic probe at 0 ° orientation as seen in Figure 8. No measurable changes were detected in any of the plates when the probe was oriented at



A. Above, Overall view of four-point loading facility and strain, load, and ultrasonic velocity measurement instruments.

a. 386 PC computer based ultrasonic velocity measurement system.
b. Digital load readout from load cell.
c. Strain gauge meters & interface.
d. Gated pulse-echo ultrasonic instrument.
e. 60,000 lb load test machine set-up for four-point loading of steel, aluminum, and titanium plates.
f. Test plate in four-point bending with strain gauges and ultrasonic velocity measurement module.



B. Above, Details of plate loading and ultrasonic velocity measurement module.

a. Arrows indicate direction of forces on plate.
b. Test plate.
c. Transmit ultrasonic transducer.
d. Receiver transducers.
e. Dial indicator showing deflection of plate (strain gauges are mounted on top of plate).

Figure 8. Reinhart & Associates, Inc. strain measurement/load test facility, R&A laboratory, Austin, Texas.

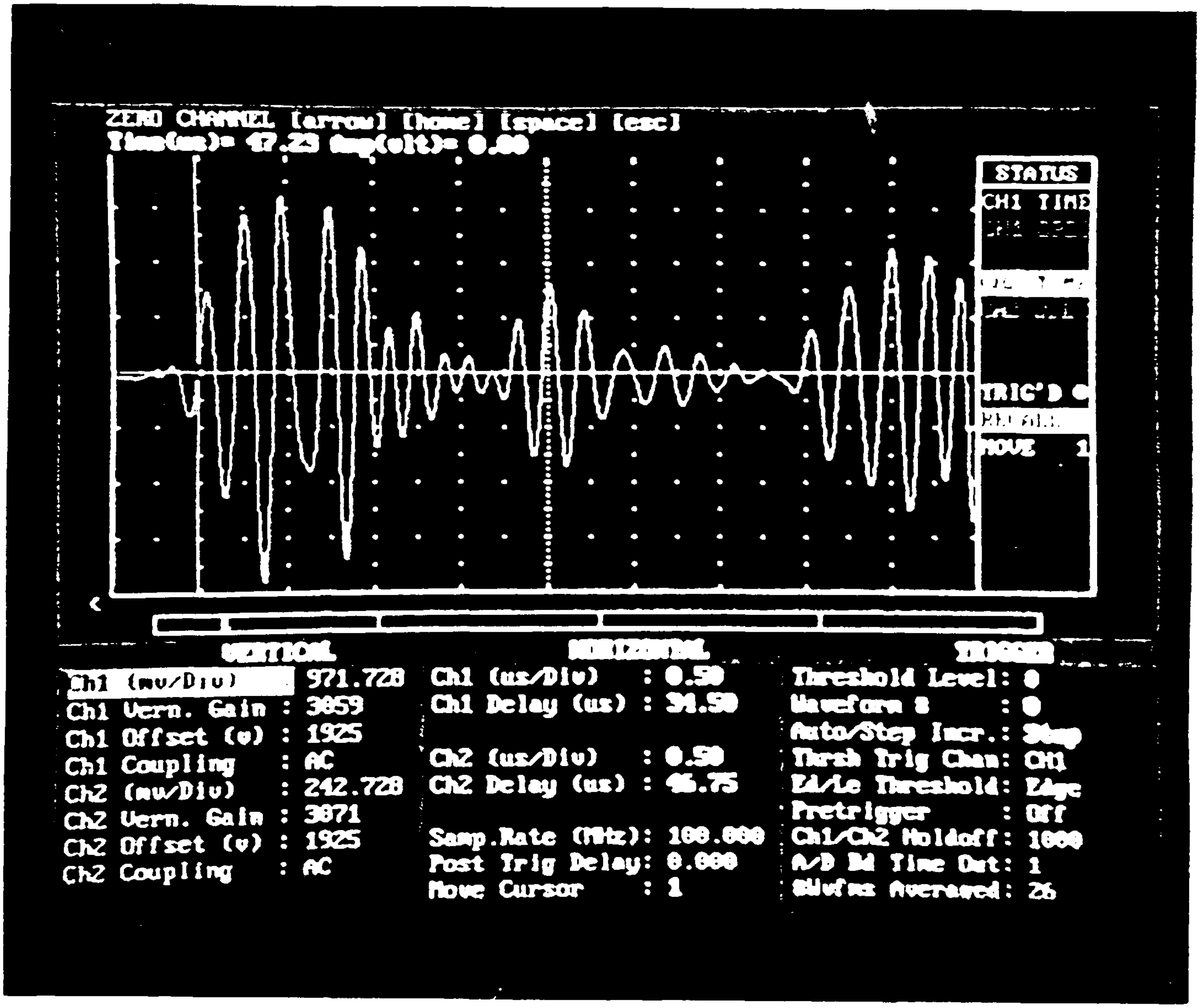


Figure 9. Typical waveform display obtained by using a 386-PC and an analog to digital card. The waveform was obtained using a 5 MHz ultrasonic probe on the 6061-T651 aluminum plate

Table II. Acoustoelastic constants (AEC) obtained from tension tests.

Material Specification	Probe Orientation (deg)	Frequency (MHz)	AEC
Ti-6Al-4V	0°	01.00	-0.8780
		02.25	-1.0042
		05.00	-1.0406
		10.00	-1.0696
	45°	01.00	-1.2416
		02.25	-1.4104
		05.00	-7.1784
		10.00	-3.0618
	90°	01.00	-3.3368
		02.25	-9.5385
		05.00	-1.9194
		10.00	Noisy Signal
Al-6061-T651	0°	01.00	-2.7184
		02.25	-2.6937
		05.00	-2.9719
		10.00	-3.5185
	45°	01.00	-3.4785
		02.25	-5.0599
		05.00	-3.4300
		10.00	-3.6917
	90°	01.00	-1.6523
		02.25	-1.6371
		05.00	-1.6330
		10.00	No Change
4340 Steel	0°	01.00	-3.0491
		02.25	-3.1312
		05.00	-3.0195
		10.00	-3.0527
	45°	01.00	-1.6552
		02.25	-3.3821
		05.00	-6.8423
		10.00	-4.8796
	90°	01.00	No Change
		02.25	No Change
		05.00	No Change
		10.00	No Change

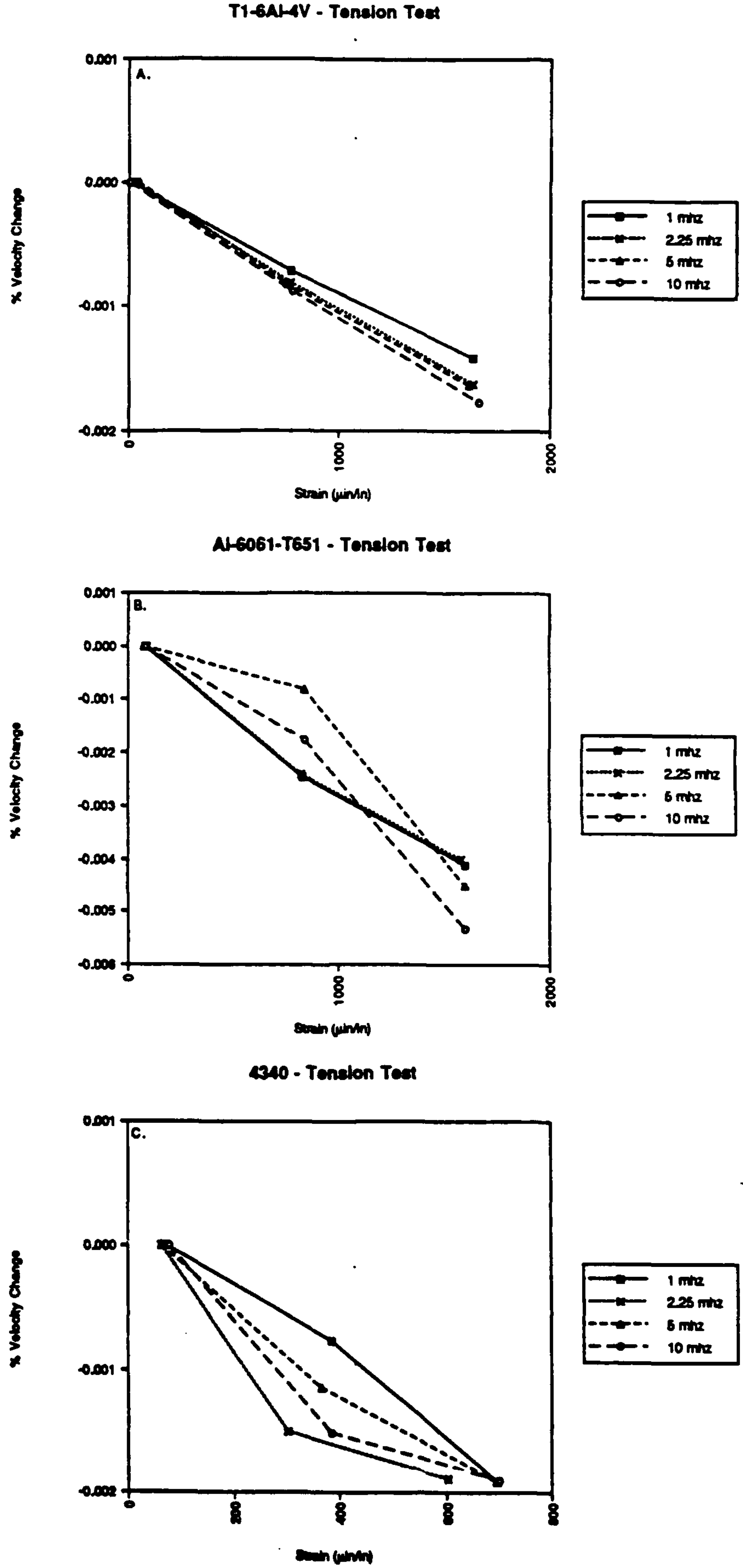


Figure 10. Longitudinal wave velocity change as a function of applied tensile strain measured parallel to the applied load (0° probe orentation).

Table III. Load, deflection, and strain measured during the 4-point bending test.

Load (lb) (P) (Measured)	Actual Load (lb) (p/2)	Measured Maximum Deflection (in)					
		Ti-6Al-4V	ε*	Al-6061-T651	ε*	4340 Steel	ε*
0	0	0.000	0	0.000	0	0.000	0
500	250	0.027	690	0.008	296	0.003	
1,000	500	0.055	1,226	0.016	594	0.007	256
2,000	1,000	0.093	1,951	0.032	1,138	0.013	488
3,000	1,500			0.048	1,688		718
4,000	2,000			0.064	2,220	0.026	947
5,000	2,500			0.074	2,672		1,181
6,000	3,000					0.042	1,420
7,000	3,500					0.050	

ε* = Strain (μin/in)

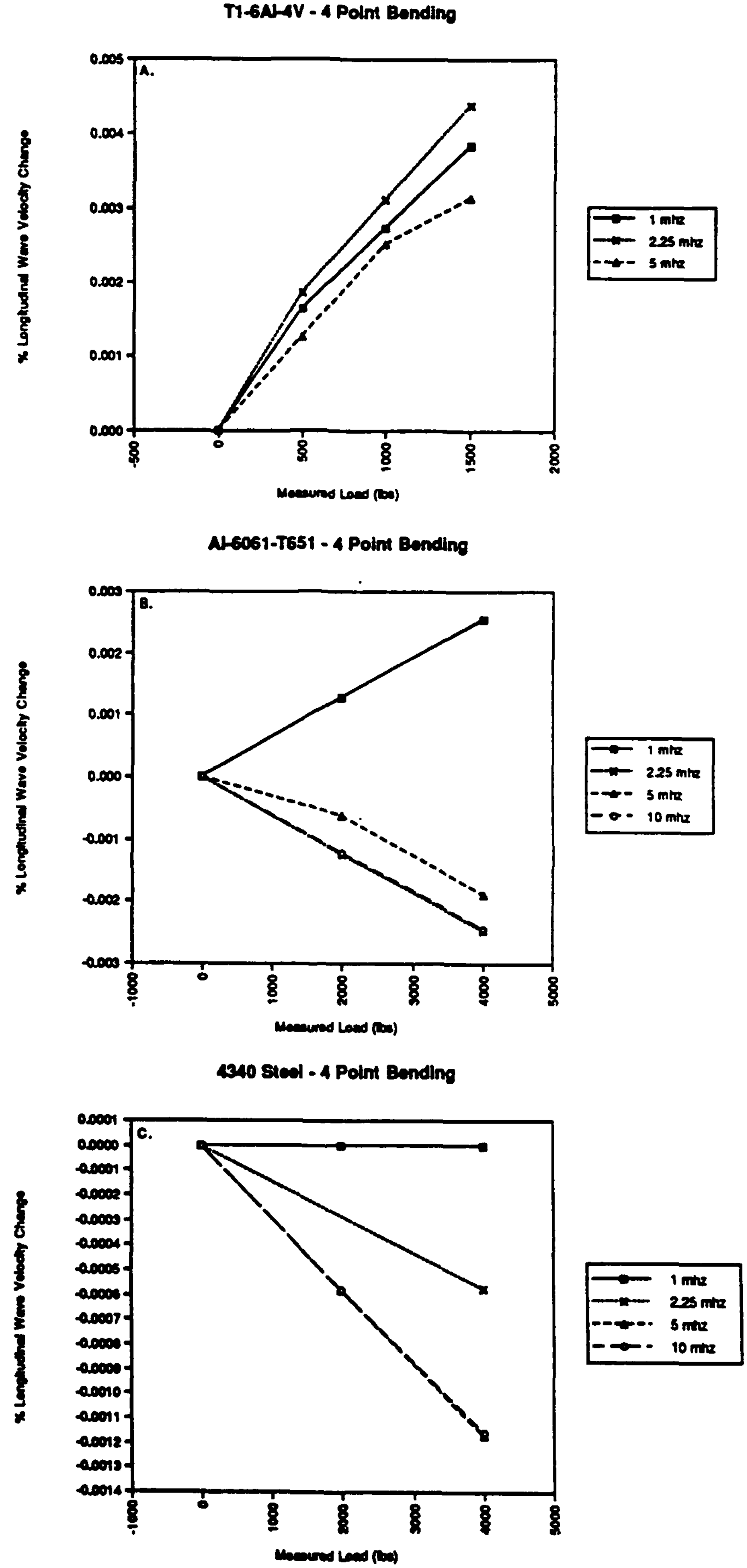


Figure 11. Longitudinal wave velocity change as a function of applied load from a 4-point bending (Moment = (Load/2)x3.5 in.).

90 °; thus, the velocity (travel time) at 90 ° provided a reference that is independent of the applied stress. This suggests that velocity ratios of 0 ° and 90 ° could be used to monitor absolute stress changes in uniaxial bending.

Figure 11 A shows the data obtained from testing the Ti-6Al-4V plate. It essentially shows a longitudinal wave velocity increase as the plate is bent. It is possible that this unexpected reversed trend is caused by the interaction of the CRLW and 2P waves with the bottom part of the plate where the stress is compressive. The reversed effect may be enhanced because this plate thickness is only 0.25 inch.

Figure 11 B shows the data for the Aluminum 6061-T651 plate. It shows that for all the frequencies except 1 MHZ, the longitudinal wave velocity decreases as the plate is bent. This follows the expected trend since the CRLW is propagating close to the top surface wherein the stress is tensile. The 1 MHz data deviates from the expected trend because it probably is interacting more with the bottom part of the plate at very low frequency and long wavelength.

Figure 11 C displays the data obtained by bending the 4340 steel plate. It shows the expected trend for all of the frequencies, i.e., the higher the frequency, the larger the effect of the tensile stress induced by bending of the top surface. The lower the frequency the less the effect, since ultrasound tends to average the effect of the tensile and compressive stress present in the bent plate.

5.0 CONCLUSIONS AND RECOMMENDATIONS

After the mathematical modeling and after two tests performed to establish how viable it is to measure stress at the surface and interior of a plate, it was found that:

The use of water as couplant improve the repeatability of the four-point bending test.

The CRLW wave followed the expected trend of stress changes through the thickness of a 4340 steel plate and 6061-T651 aluminum plate of 0.50 inch thickness.

The expected trend measured in a Ti-6Al-4V plate was reversed and a more detailed study needs to be performed to fully characterize this material for thicker plates, i.e., > 0.25 inch.

There exists a possibility of using the 2P wave as a reference wave and the CRLW to monitor material properties and/or stress, provided the propagating medium is a layer of finite thickness.

It is recommended for Phase II of this project to proposing using a set of material samples containing residual stress to be studied using the CRLW technique and compare with the hole-drilling techniques.

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